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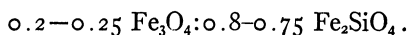
THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

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IV

MAGNETITE

Magnetite and olivine (with fayalite).—As discussed in “Silikat-schmelzlösungen,” I (1903), the individualization boundary between magnetite and fayalite (reckoned by weight) lies at about:



Near the same boundary, probably with somewhat less magnetite and somewhat more olivine, we find in the “titanomagnetite”-olivinites, chiefly consisting of the so-called “titanomagnetite,” which is a mechanical mixture of magnetite and ilmenite, and of olivine, the latter with proportions intermediate between Fe_2SiO_4 and Mg_2SiO_4 (partly stoichiometrically about $0.4 \text{ Fe}_2\text{SiO}_4 \cdot 0.6 \text{ Mg}_2\text{SiO}_4$, partly still more Fe_2SiO_4 and less Mg_2SiO_4). As described several years ago by earlier investigators, among them also myself, the olivine in these rocks appears partly porphyric in the “titanomagnetite” when it is quite abundant. As an example we may take the “titanomagnetite”-olivinite from Cumberland in Rhode Island, according to C. H. Warren¹ with an average mineralogical composition of 46.1 per cent olivine ($0.39 \text{ Fe}_2\text{SiO}_4 \cdot 0.61 \text{ Mg}_2\text{SiO}_4$), 20.7 magnetite, 18.6 ilmenite, 9.2 labradorite (Ab_3An_4), 3.6 spinel (and in addition a little Or and sulphide).

The specimen at my disposal (Fig. 27) gives the same proportions between olivine and magnetite plus ilmenite, but less labradorite and less spinel. The olivine shows a more or less well-developed idiomorphic contour against the iron-ore minerals.

¹ *Amer. Jour. of Sci.* (1908), p. 175.

A few quite small individuals of magnetite or ilmenite also appear in the olivine.

The sequence of crystallization cannot here be explained in detail, but so much can be said, that the olivine commenced crystallizing at a very early stage, and certainly not much magnetite

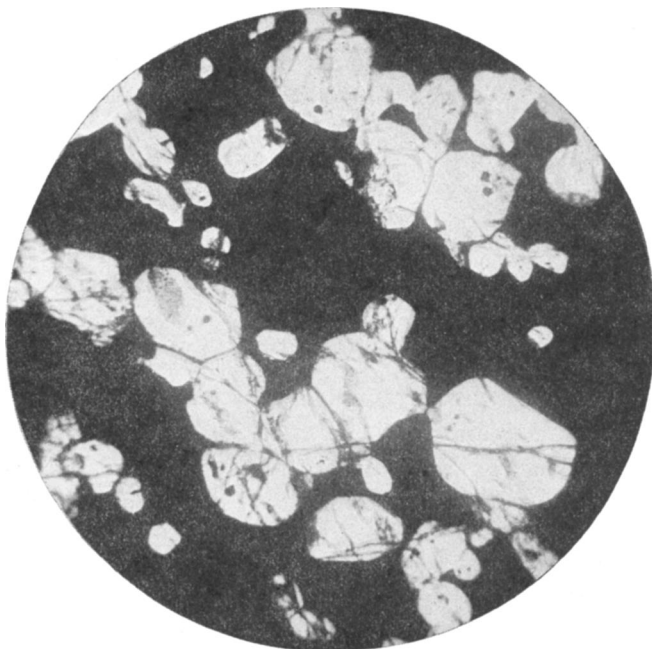


FIG. 27.—Photomicrograph (25:1) of "titanomagnetite"-olivinite from Cumberland, Rhode Island. White=olivine, black="titanomagnetite."

or ilmenite can have been solidified before the commencement of crystallization of the olivine.

Very interesting in structural respect is a "titanomagnetite"-olivinite (Fig. 28) from Fiskaa in Söndmøre, Norway, consisting of about 50 per cent olivine (according to optical investigations $0.35-0.4 \text{ Fe}_2\text{SiO}_4:0.65-0.6 \text{ Mg}_2\text{SiO}_4$); about 40 per cent magnetite plus ilmenite, about 5 per cent spinel; and in addition locally a little hypersthene.

The olivine, with no sign of an idiomorphic contour, shows in nearly every individual an intimate intergrowth with the iron ore,

chiefly magnetite, giving in this manner a form of structure nearly identical with graphic granite or with coarse-grained granophyre. This must be due to a *simultaneous* crystallization of the olivine and the iron ore, especially the magnetite, and the proportion by weight in the intergrown individuals gives about 0.25



FIG. 28.—Photomicrograph (25:1). “Titanomagnetite”-olivinite from Fiskaa, Söndmøre, Norway. White=olivine, black=titanomagnetite. The small gray grains in the photograph are spinel.

magnetite:0.75 olivine, this representing a point or a line on a quite complicated eutectic boundary curve.

Magnetite in gabbro, norite, anorthosite, etc.—As is well known, and still believed by many petrographers, Rosenbusch made the assertion that the oxidic iron ores, magnetite, ilmenite, etc., always belong to the oldest segregations, and crystallized before the solidification of the silicates. This assertion, however, is not correct with regard to the gabbroic rocks, for when only little magnetite (and ilmenite) is present, the crystallization of iron ore does not

commence until the surplus silicate mineral has solidified, so that the quantity of Fe_3O_4 (and FeTiO_3) in the rest of the magma has reached a certain amount.

In this connection we choose as an example a rock with a surplus of *plagioclase*. This has previously been described in detail by myself, and treated above, viz., the porphyritic labradorite-norite from Flakstadöen in Lofoten. In proportion to the whole rock 23 per cent labradorite was solidified first, and the crystallization of iron ore, simultaneously with the continued crystallization of plagioclase only commenced when the quantity of iron ore had reached 8.1 per cent $\text{Fe}_3\text{O}_4 + 0.9$ per cent FeTiO_3 . If we leave out of consideration the components present in small quantity (biotite, apatite, and ilmenite), we obtain the following figures for the commencement of crystallization of the magnetite: about 8.5 per cent magnetite; about 64.5 labradorite; about 13.5 hypersthene; about 13.5 diallage. This represents a point or a line on the individualization boundary between the labradorite and magnetite in a very complicated system, magnetite:labradorite (42 Ab, 6 Or, 52 An):hypersthene:diallage (the two last with many separate components).

In hyperitic-structured gabbro and norite (with olivine gabbro and norite), where at an early stage *much plagioclase* had solidified in the well-known lath-shaped individuals, the magnetite (and ilmenite), when present only in a quantity as small as 1-2 per cent, shows no sign of idiomorphic contour.

On the contrary, the magnetite here only appears as an intervening mass chiefly between the plagioclase individuals (see Figs. 29 and 30), indicating that much plagioclase had already solidified before the magnetite commenced forming.

In this connection we refer to a treatise by S. Foslie (Kristiania) on "The Titanic Iron Ore Deposit at Ramsøy and Its Processes of Differentiation,"¹ where is described a hornblende gabbro, containing about 58 per cent plagioclase, 2.5 per cent magnetite, 31 per cent hornblende, 6.5 per cent biotite, and 2 per cent quartz, with the magnetite formed later than the plagioclase. His photomicrograph, Table I, Figure 1, accords quite well with Figures 29-30 in this paper.

¹ *Geol. Survey of Norway, Aarbog for 1913.*

In the norites, relatively *rich in hypersthene* but quite poor in magnetite (and ilmenite), the crystallization of iron ore did not commence until some part of the hypersthene had solidified. As an example we choose a norite from Skougen in Bamle, which, according to the chemical analysis (see the section on norite in Part II), contains 1.09 per cent TiO_2 , 1.44 Fe_2O_3 , and 9.42 FeO . The mineralogical composition is about 47 per cent hypersthene (with a little secondary hornblende), 3 per cent biotite, 48 per cent labradorite, and about 1-2 per cent iron ore, and in addition a little



FIG. 29.—Photomicrograph (21:1)

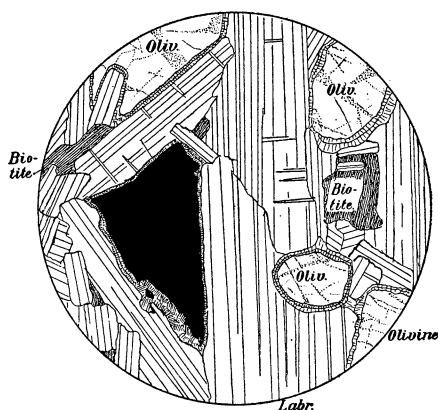


FIG. 30.—Drawing (21:1)

Hyperitic-structured olivine-gabbro from Elverum, Norway. Consisting of *ca.* 65 per cent labradorite, 10 per cent olivine, 10-15 per cent diallage, 3-5 per cent biotite, and *ca.* 2 per cent magnetite (with a little ilmenite).

apatite and pyrite. An essential part of TiO_2 and Fe_2O_3 enters into hypersthene and biotite. In most parts of the thin section (see Fig. 13) iron ore is lacking as it only appears in a few places.¹ Here the hypersthene shows an idiomorphic contour against the magnetite, and this applies especially to the relatively *small* individuals of hypersthene, which partly have an entirely straight crystallographic boundary against the magnetite (with ilmenite).

The latter, on the contrary, shows no signs of idiomorphic outlines. Some part of the hypersthene must thus have solidified before the formation of the magnetite. Since especially the *small*

¹ For this reason we are not able to determine the quantity of the iron ore with precision by a planimeter calculation of the thin section.

individuals of hypersthene show marked idiomorphism against the magnetite (and ilmenite), the crystallization of the iron ore seems to have begun when only the lesser part of the hypersthene had solidified.

Further we find here and there in the same thin section some small crystals of pyrite, surrounded by a thin wreath of magnetite (or "titanomagnetite"). The pyrite accordingly has here served as *Fixkörper* for the deposit of magnetite, which also indicates a solidification of the magnetite at a relatively early stage, while the essential part of the rock still remained in the liquid phase.



FIG. 31.—Photomicrograph (30:1)



FIG. 32.—Photomicrograph (45:1)

From the same thin section of norite from Skougen shown in Figure 13, containing 1-2 per cent "titanomagnetite." Figures 31 and 32 represent two places with much magnetite (and ilmenite), besides hypersthene, a little hornblende, and biotite.

In the olivine-hyperites, *rich in olivine*, with about 25-30 per cent olivine, only 1-2 per cent "titanomagnetite," much plagioclase (labradorite, quite rich in An), and some diallage, etc., the crystallization, as mentioned above, commenced with the solidification of some olivine, and only then did the "titanomagnetite" commence crystallizing as a deposit on the olivine crystals which acted as a *Fixkörper*. We refer to Figure 33, drawn with the detailed help of a photomicrograph.

We have here treated several gabbros and norites with only *very little* magnetite (and ilmenite). In the corresponding rocks

with a somewhat *larger quantity* of magnetite (and ilmenite) the sequence of crystallization, on the contrary, is different. Here we find idiomorphic crystals, especially octahedrons of magnetite, appearing in the silicate minerals first crystallized. In gabbroidic rocks with much hypersthene, diallage, or olivine, the magnetite seems already to have commenced its crystallization at about 4 per cent Fe_3O_4 , and about simultaneously with the first individualized

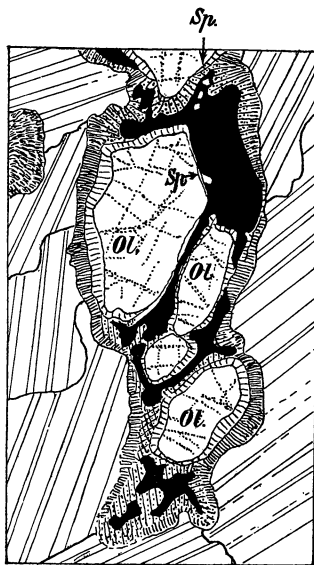


FIG. 33.—Hyperitic-structured olivine-gabbro from Langö, near Kragerö, Norway. Contains about 25 per cent olivine (Ol.), *ca.* 1–2 per cent magnetite with ilmenite (black), 60 per cent labradorite, 12 per cent diallage, 2 per cent brown hornblende, 0.01–0.02 per cent spinel (Sp.) in the magnetite, very little apatite. Drawn partly from photograph and partly from nature.

Magnetite (with ilmenite), younger than the olivine. Olivine with reaction rims against the labradorite. (In the inner zone hypersthene, in the exterior zone green hornblende and spinel.) Between the magnetite and the labradorite is a reaction rim consisting chiefly of light-brown hornblende. (28:1.)

ferromagnesian silicate. This boundary, 4 per cent Fe_3O_4 , is, however, quite approximate, and it is to a great extent dependent upon the composition of the magma.

In gabbro rocks, rich in plagioclase, and in anorthosite gabbros, the boundary seems to lie somewhat higher, viz., according to

my earlier determination of the rock from Lofoten described above, at about 8-9 per cent magnetite.¹

We here interject the remark that the simultaneous crystallization of "titanomagnetite" and hypersthene, diallage, or olivine, taking place at an early stage of crystallization in norites and gabbros (with olivine gabbros, etc.) which carry much ferromagnesian silicate and some few per cent of iron ore, explains how the well-known magmatic differentiation products of "titanomagnetite" in these rocks are characterized by an enrichment of "titanomagnetite" plus the ferromagnesian silicate in question, consequently hypersthene, diallage, or olivine respectively.

Magnetite in the granitic rocks.—Here the magnetite, when present in a quantity of at least 0.5 or 1 per cent, commences crystallizing at a very early stage, viz., a little later than the apatite, which, as is known, often appears as idiomorphic needles in the magnetite, but on the other hand earlier than the biotite or other ferromagnesian silicates which, in part, were deposited on the *Fixkörper* magnetite.

At this early stage, however, the whole quantity of magnetite was not crystallized. We are thus able to detect exceedingly small magnetite individuals in the groundmass, for example, in quartz porphyres; and the many analyses (Nos. 14c-29c) of glass, ground-mass, and intervening mass between the orbicules, etc., in granite without exception show a little Fe_2O_3 and FeO . In the granitic eutectic which at last results, there usually seems to appear about 1 per cent Fe_2O_3 and FeO , of which, however, a little is bound up with the small quantity of ferromagnesian silicate, and a little Fe_2O_3 probably also appears as a solid solution in the feldspar. The magnetite seems to appear in the final eutectic in a quantity of about 0.5 per cent.

For the magnetite as well as for the ferromagnesian silicates the solubility is much less in the granitic than in the gabbroidic magmas.

Spinel.—Magnetite and spinel (pleonast and hercynite) ($\text{Mg, Fe}(\text{Al}_2, \text{Fe}_2)\text{O}_4$, with at most about 7-10 per cent Fe_2O_3 , but sometimes with more FeO than MgO , form between them a series of

¹ Foslie (*loc. cit.*) sets the boundary still somewhat higher. This, however, is not in accordance with my investigations of the problem in hand.

discontinuous mix-crystals with a eutectic boundary consisting of about 2.5-3 per cent spinel:97.5-97 per cent magnetite (cf. my treatise, cited p. 2, "Über das Spinell:Magnetit-Eutektikum," 1910).

In the igneous rocks, containing *primary* spinel, this mineral, as is well known, belongs to the very first stage of crystallization when it is present in at least about 0.1 per cent by weight. But if the quantity of spinel sinks still lower the case is different. As an example we may mention that in the olivine-hyperite, illustrated in Figure 33, where first some olivine crystallized and later a little magnetite, some quite small individuals of spinel often appear in the magnetite. The spinel forms about 1 per cent of the magnetite, and since the latter forms 1-2 per cent of the entire rock, the quantity of spinel may consequently be set to 0.01-0.02 per cent. And this minimal quantity of spinel did not crystallize until mineral No. 1, in this case the olivine, had commenced forming.

Further we shall mention an ilmenite-norite from Storgangen near Soggendal (Ekersund), consisting of about 40 per cent ilmenite, 40 per cent hypersthene, 20 per cent labradorite, and in addition 1-2 per cent biotite, about 0.2 per cent pyrite, and about 0.1 per cent spinel. The latter is intensely green and must be termed hercynite.

The pyrite appears in small cubes (with edges 0.1-0.3 mm.) and on these quite small spinels (0.04-0.1 mm. large) have grown. These were deposited on the crystals of pyrite,¹ which in this manner served as *Fixkörper* in the still molten magma. The small spinels show an octahedron boundary against the surrounding, later mineral—ilmenite, labradorite, or hypersthene. FeS_2 as well as $(\text{Mg, Fe}) (\text{Al}_2, \text{Fe}_2)\text{O}_4$ were so little soluble in this magma that, although present in so small a quantity, they commenced crystallizing at an earlier stage than the silicates and the iron ore, but in such a manner that at the very first stage some pyrite solidified, and then, at somewhat lower temperature, the spinel.

The essential part of the *apatite* crystallizes, as is well known, at a very early stage. Sometimes, in the same thin section (Fig. 35), we may find a crystal of pyrite serving as *Fixkörper* for the deposit

¹ The same sequence of crystallization, spinel later than pyrite, I have mentioned also in an earlier treatise, see *Zeitschr. f. prakt. Geol.* (1900), p. 238, Fig. 39.

of apatite, and in other places a crystal of apatite serving as *Fixkörper* for a deposit of pyrite, showing that the two minerals were formed practically simultaneously. At the same weight (as 0.1-0.25 per cent) of apatite, pyrite, and spinel, the crystallization of apatite and pyrite seems to commence at a somewhat earlier stage than the crystallization of spinel.



FIG. 34.—From an ilmenite-norite from Storgangen, near Soggendal, Norway. Three crystals of pyrite on which have been deposited small crystals of spinel, lying in ilmenite. (40:1.)

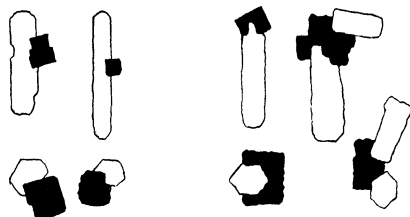


FIG. 35.—From a uraltic quartz-norite from Flaad, Evje, Norway. Black = pyrite, white = apatite. (40:1.)

PYRITE AND PYRRHOTITE

According to the precision-investigations by E. T. Allen, I. L. Crenshaw, and I. Johnson,¹ at the Geophysical Laboratory in Washington, the melting-points are for FeS, $1170 \pm 5^\circ$; for pyrrhotite, 1183° (to 1187°).

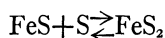
The analyses of pyrrhotite show, as is well known, a surplus of S above the proportion Fe:S, which the investigators mentioned (1912) interpreted to indicate that some S entered as a solid solution in FeS. Soon after, Docent C. W. Carstens,² of Trondhjem, pointed out that what enters in the solid solution must be FeS₂ and not S, an interpretation which, independently of Carstens' statement,

¹ *Amer. Jour. of Sci.*, Vol. XXXIII (1912).

² *Norsk geologisk tidsskrift*, Vol. III (1914).

was also later indicated by Posnjak, Allen, and Mervin¹ at the Laboratory in Washington.

That this is really so, appears theoretically through the fact that the process:



is reversible. FeS in solid solution is able to absorb as much as 23 per cent FeS₂. The solubility of FeS in FeS₂ is, however, nil or minimal.

For the discontinuous binary mix-crystal system, only two cases exist, viz., either type V (with a eutectic) or type IV (with a bending-point). By the following observations we may determine to which of these two types the system FeS:FeS₂ belongs.

1. The pyrrhotite has a relatively low melting-point not only at the pressure of one atmosphere but, as appears from the statement given below, also at the high pressures prevailing in deep-seated magmas. The pyrite, on the other hand, crystallized in the deep-seated magmas at a very early stage and, consequently, at a relatively high temperature. The pyrite, accordingly, at high pressure may exist in the solid phase at a much higher temperature than the melting-point of the pyrrhotite. The genesis of the intrusive pyrite deposits proves that FeS₂ at very high pressure may also occur in the liquid phase. Pyrite consequently (at high pressure) has an even much higher melting-point than pyrrhotite.

2. Pyrrhotite (FeS with FeS₂ in solid solution, with as much as 23 per cent FeS₂:77 per cent FeS) has a higher melting-point (*G* on Fig. 36) than FeS. This already proves that the system belongs to type IV.²

3. We have a confirmation of this in the fact that in the ore deposits of pyrite and pyrrhotite, formed by magmatic differentiation, we always find, irrespective of the proportion by weight between the two sulphides, the sequence of crystallization, (1) pyrite (2) pyrrhotite, but, on the other hand, never the inverse sequence of crystallization, (1) pyrrhotite, and (2) pyrites. Regarding the

¹ *Amer. Jour. of Sci.*, Vol. XXXVI (1915).

² See my résumé-treatise, "Die Sulfid-Silikatschmelzlösungen" (1917).

resorption phenomena at the stage I to K we refer to the explanation in a later paragraph.

With regard to the structure of the deposits of *pyrrhotite-hypersthénites*, *-olivinites*, *-norites*, etc., formed by magmatic differentiation, I refer to my earlier publication "Die Sulfid-Silikat-schmelzlösungen" (in *Norsk geologisk tidsskrift*, 1917). I shall here only give a short summary.

We shall commence with the per se very rare *pyrrhotite-olivinites*, and as an example choose the deposit at Bruvand (Ballangen,

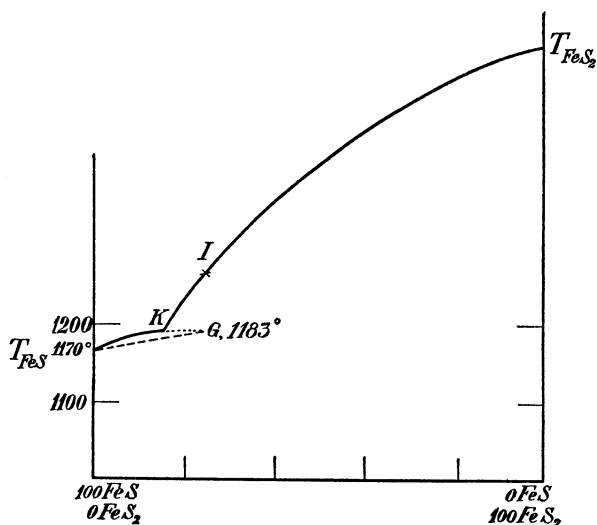


FIG. 36.—The binary system FeS:FeS₂, at high pressure. (The melting-points for FeS and pyrrhotite refer to low pressure.)

Ofoten in Norway) where the olivinite carries about 8 per cent sulphides, which we for brevity's sake shall term "nickel-pyrrhotite" (pyrrhotite with some pentlandite, chalcopyrite, and pyrite, in the present case with about 6–7 per cent nickel).

The rock consists, with deduction of the sulphides, of about 85–90 per cent olivine (according to chemical analysis $0.12 \text{ Fe}_2\text{SiO}_4 \cdot 0.88 \text{ Mg}_2\text{SiO}_4$, and accordingly quite poor in iron and not the least serpentinized), and in addition a little bronzite, primary hornblende, etc. The sulphides are not quite evenly distributed over the whole rock, but accumulated in small patches, especially on the boundary between the olivine grains (see Fig. 37).

This is most clearly shown in the thin sections (see Figs. 38 and 39), where the olivine individuals against the pyrrhotite show more or less well-developed idiomorphism; however, such that the edges are somewhat rounded.

We especially remark the quite good idiomorphism of the *small* olivine individuals against the pyrrhotite.

The rather common segregations of *pyrrhotite-hypersthene* in hypersthene-rich norites carry from 10–20 to 50–60 per cent of nickel-pyrrhotite. Besides the sulphides, they may carry hypersthene alone or hypersthene accompanied by more or less plagioclase, etc. The hypersthene here appears as porphyritic crystals in the pyrrhotite; the boundary planes of the crystals, however, usually are somewhat rounded, with small bends, etc. (see Figs. 40–43).

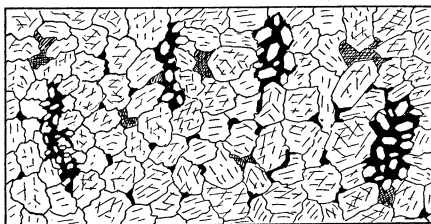


FIG. 37.—Pyrrhotite-olivine from Bruvand, Ofoten, Norway. Light-structured mineral = olivine, dark-structured = bronzite and hornblende, black = pyrrhotite. (Natural size.)

A corresponding structure may also be observed in a *pyrrhotite-norite* from Dyrhaug in Værdalen, chiefly consisting of labradorite (Ab_1An_2 , occasionally with zonal structure from about $\text{Ab}_{28}\text{An}_{72}$ in the kernel to about $\text{Ab}_{40}\text{An}_{60}$ in the exterior zone) and nickel-pyrrhotite (see Figs. 44, 45).

The structure here described can only be explained to show that the *olivine* (Figs. 37–39), the *hypersthene* (Figs. 40–43), and the *labradorite* (Figs. 44–45) have crystallized at an earlier stage than the *nickel-pyrrhotite*.

And this is in best conformity with the intervals of the melting-points, calculated for the different minerals at atmospheric pressure, and only quite unessentially changed at higher pressure (see a following paragraph).

The melting-point of pyrrhotite is 1183° (or 1187°), and for a sulphide mixture, consisting of predominant pyrrhotite, 3–6 per cent pyrite, some chalcopyrites, and some pentlandite, we may fix the crystallization interval from about 1190° (or about 1200°), for the commencement of crystallization of the pyrite, down to,

or perhaps a little below 1150° for the last remnant of sulphides, consisting of chalcopyrite with some pyrrhotite and some pentlandite.

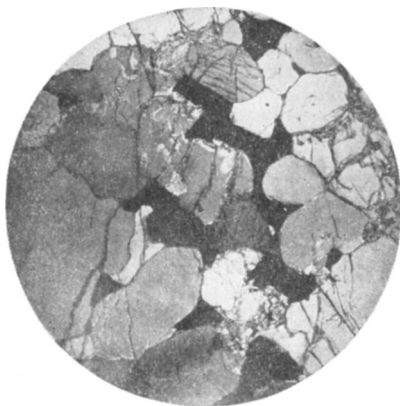


FIG. 38.—Photomicrograph between crossed nicols (15:1).

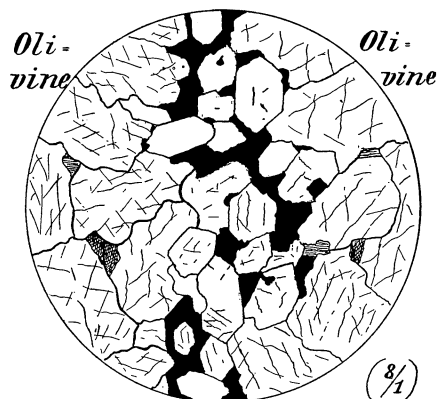


FIG. 39.—Drawing (8:1)

Pyrrhotite-olivinite from Bruvand (cf. Fig. 37). Two different portions.



FIG. 40.—Photomicrograph (17:1)



FIG. 41.—Photomicrograph (17:1)

Pyrrhotite-hypersthenite from Romsaas (Fig. 40) and Messel, near Arendal (Fig. 41). In Figure 40 besides pyrrhotite there is only hypersthene. In Figure 41 besides hypersthene there is also a little labradorite (upper left). In Figure 41 two small holes in the thin section appear white.

For an olivinite, consisting of predominant olivine ($0.12 \text{ Fe}_2\text{SiO}_4 \cdot 0.88 \text{ Mg}_2\text{SiO}_4$) and a little orthorhombic pyroxene

(bronzite), likewise quite iron-poor, and iron-poor hornblende, we may reckon a crystallization interval from about 1500° down to 1400° or somewhat lower.

For hypersthene (with about $0.3\text{FeSiO}_3 \cdot 0.7\text{MgSiO}_3$) the crystallization interval, according to the earlier approximate determinations, lies at about $1300\text{--}1200^{\circ}$.

In a silicate mixture, consisting of predominant labradorite (Ab_1An_2) and a little diallage and hypersthene, the labradorite

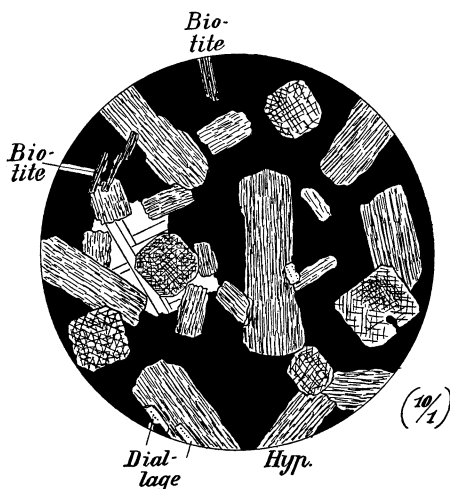


FIG. 42.—From Romsaas (10:1)

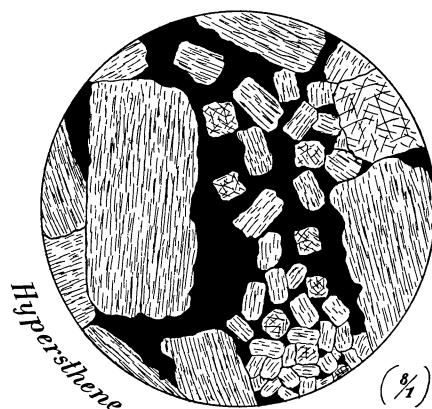


FIG. 43.—From Messel (8:1)

Drawings of pyrrhotite-hypersthenite. In Figure 42 besides hypersthene there is a crystal of labradorite (with twinning lamellae), a little biotite, and traces of diallage.

will commence crystallizing at about 1450° , and the essential part of the rock will be solidified at about $1300\text{--}1250^{\circ}$. The residual magma, present in quite small quantity, will crystallize along a eutectic boundary-line, down to about 1200° or probably a trifle lower. For the three pyrrhotite rocks just mentioned, the silicates must consequently in two cases have crystallized entirely and in the third case either entirely, or nearly entirely, while the sulphides were still in the liquid phase.

At temperatures of 1500° , 1400° , and 1300° melted silicate of the composition of olivinite, hypersthenite, or labradorite-rich

norite, may contain in solution only quite a small quantity of FeS (and still less of Cu_2S and NiS). Melted sulphide, consisting of FeS, etc., may, at the temperatures mentioned, dissolve only a trifle silicate.¹ The pyrrhotite-rich rocks mentioned must therefore during the interval of crystallization have consisted of *two liquids* (*two liquid phases*), *one silicate phase* with only a little dissolved sulphide and *one sulphide phase* without or with only a very inconsiderable amount of dissolved silicate.



FIG. 44.—Photomicrograph between crossed nicols (15:1).

Pyrrhotite-norite from Dyrhaug, Skjækerdalen, Værdalen, Norway (cf. Figs. 20 and 21). Porphyritic labradorite in nickel-pyrrhotite, besides a little hypersthene, diallage, and biotite.

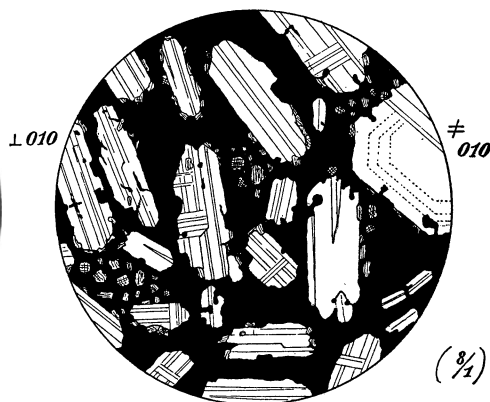


FIG. 45.—Drawing (8:1)

The common norites and gabbros usually contain 0.1–0.4 per cent S, which corresponds to about 0.25–1 per cent pyrrhotite, which, however, occasionally is accompanied by some pyrites. The pyrrhotite is here usually not evenly distributed in quite small individuals over the whole rock, but most often accumulated in somewhat larger lumps with a diameter of 0.5, 1, or 2 mm., occasionally more (see, for instance, Fig. 10).

Against the pyrrhotite the hypersthene as well as the diallage and labradorite here also appear with idiomorphic outlines. As an example we refer to Figures 12 and 21 and to Figure 46 from a

¹ See "Sulfid: Silikatschmelzlösungen," I (1919).

norite from Erteli, Norway, which, according to the analysis of the entire specimen, only contains 0.07 per cent S=0.18 per cent pyrrhotite, here and there accumulated in small lumps.

For the photomicrograph was chosen a locally pyrrhotite-rich part of the thin section, otherwise free from pyrrhotite. That pyrrhotite also crystallized last in common norites and gabbros is due to the circumstance that the intervals of the crystallization



FIG. 46

FIG. 46.—Photomicrograph between crossed nicols (15:1). Pyrrhotite in norite from Erteli, from the same thin section as Figures 15 and 16. The rock contains 0.07 per cent S. Figure 46 is from a portion rich in pyrrhotite.

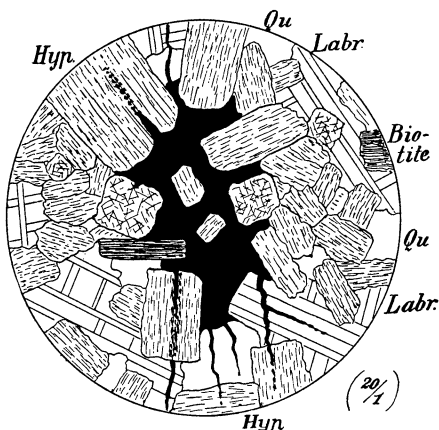


FIG. 47

FIG. 47.—Quartz-norite from Romsaas, Norway (20:1). Illustrating a portion rich in pyrrhotite, from the same thin section as Figure 10. The hypersthene, biotite, and labradorite show idiomorphic contours against the pyrrhotite, and small veins of pyrrhotite cross the silicates.

for the silicates lay somewhat above, but for the pyrrhotite a little below, 1200°.

As well in pyrrhotite-hypersthenites and -norites, etc. with quite much pyrrhotite, as in the common norites, etc. with only about 0.2–0.5 or 1 per cent pyrrhotite, we frequently find *veins of pyrrhotite* branching off from relatively larger accumulations of this mineral, and intersecting the neighboring minerals.

We refer to Figure 47, where we see quite thin veins of pyrrhotite intersecting the hypersthene and the labradorite, which otherwise

show idiomorphic contours against the pyrrhotite. This phenomenon is due to the fact that the melted FeS even at *so low a temperature* as about 1200° is very thin fluid.¹

FeS_2 is so little soluble in the silicate magma that the limit of the solubility, when only about 0.1–0.2 per cent FeS_2 is present, is usually reached by the cooling of the magma to somewhat above the upper boundary of the crystallization interval of the silicates. The melting-point of FeS_2 lies (at high pressure) at a still higher temperature. FeS_2 consequently, in the common igneous rocks, separates in the *solid* phase.

The solubility of FeS in silicate magmas at any temperature depends, as explained in my treatise “Die Sulfid-Silikatschmelzlösungen,” on the chemical composition of the magma; the solubility under otherwise similar conditions increasing with the basicity. And as usual with dissolved substances, the solubility of FeS also increases with the temperature. In melts of gabbroidic composition, the solubility at 1350 – 1400° and at the pressure of one atmosphere is about 0.25–0.4 per cent FeS but decreases rapidly at a little lower temperature, as about 1300° . When the limit of solubility is reached by the cooling of the silicate magma, FeS accordingly separates in the *liquid* phase.

On account of the great difference existing at high pressure between the melting-points of FeS_2 and FeS , an essential difference arises with regard to the physics of the segregation: *FeS_2 crystallizes while FeS , on the other hand, separates in liquid phase* and remains in this condition till near the termination of the solidification of the rock.

The *intrusive deposits of pyrite*, which often are characterized by nearly exclusively pyrite, and which usually do not contain any pyrrhotite, prove also that FeS_2 at especially high pressure may exist in the liquid phase.

The formation of these deposits is probably due to the fact that locally in the igneous magmas so much FeS_2 has been present, that the latter at especially *high* temperature has been secreted at

¹ See “Die Sulfid-Silikatschmelzlösungen” (1917), where I have discussed the importance of the thinness of the pyrrhotite magma for the interpretation of the morphology of these deposits.

a stage above its melting-point, accordingly in the liquid phase. But the rocks normally contain so little FeS_2 that in the granites, syenites, etc., it does not secrete until below the melting-point of the mineral, consequently directly in the solid phase.

ON THE EARLY CRYSTALLIZATION OF "APATITE AND ORES"—OR
OF THE "TELECHEMIC" MINERALS

All *phosphates* (apatite and monazite with zenotime in granite-pegmatite dikes), *sulphides* (pyrite, pyrrhotite, chalcopyrite, pentlandite, etc.), *zircon*, *corundum*, *spinel*, *chromite* (in peridotites), *hematite* (and ilmenite and magnetite in the acid igneous rocks), *titanates*, *tantalates*, and *niobates* (the last ones in granite-pegmatite dikes), further *carbon* (graphite, diamond) and native *metals* (nickel-iron, platinum), as is well known, belong to the very first products of crystallization¹ in the igneous rocks. All these substances occupy an exceptional position, being extremely little soluble in silicate magmas at a temperature somewhat above the beginning of crystallization of the silicates, and this independent of their melting-points (very high in corundum and spinel; medium-high for instance in fluorine-apatite, about 1650° ; chlorine-apatite, about 1530° ; hematite, about 1560° ; and probably somewhat lower for instance in titanite, and for pyrrhotite only 1183°).

For all these *early crystallizing* minerals, which in *chemical respect diverge very considerably from the composition of the silicates*, I have in "Die Sulfid-Silikatschmelzlösungen" proposed the term "*telechemic*" minerals ($\tau\eta\lambda\epsilon$, *tele*=distant, the same root as in telegram, telephone, telepathy, etc.).

ON "REACTION RIMS"

We choose for an example the *coronation of olivine* bordering on plagioclase, described from oliviniferous gabbros, etc., by several earlier investigators, with an *inner* zone (adjoining the olivine) consisting of hypersthene, and an *outer* zone (adjoining the plagioclase) consisting of hornblende almost always associated with some amount of spinel. In addition there occurs exceptionally a third

¹ For the pyrrhotite we must change the term crystallization to segregation (to a special fluid phase).

zone, mainly consisting of garnet, immediately adjoining the plagioclase.

1. As is well known, these zones only occur on the boundary between the olivine and the plagioclase, but never between the olivine and the pyroxenes or the magnetite.

2. The zones occur not only in rocks rich in olivine in which the olivine has in a great measure crystallized earlier than the plagioclase (see, for instance, Fig. 27), but also in rocks deficient in olivine where the plagioclase, showing idiomorphic outlines against the olivine, must have crystallized earlier than the latter. I beg to refer to Figures 48-49, representing an olivine-hyperite from Elverum, Norway, consisting of *ca.* 65 per cent labradorite, *ca.* 10 per cent olivine, and *ca.* 25 per cent diallage, the labradorite having early crystallized in lath-shaped crystals, often projecting into the olivine which did not begin to form till a somewhat later stage. We fix on the fact that the coronation zones sometimes branch a little into the labradorite, in part following local transverse fissures, in part twin lamellae, and in part the boundary between various individuals of plagioclase. I further refer to the oliviniferous labradorite rock (with Ab_1An_1) illustrated by Figures 23-24, in which however, the coronation zones are so thin that they are not recognizable in the photomicrograph. High magnifying powers are here required to enable a close examination.

From the very fact that the coronation zones only occur between the olivine and the plagioclase, and are never found between the olivine and other minerals (diallage, hypersthene, etc.), it may be inferred that in rocks rich in olivine the metamorphosis (*Umbildung*) of the olivine did not take place at a conjuncture when only the olivine had crystallized while the rest were still in a molten state. The metamorphosis accordingly, as has been earlier pointed out, particularly by Frank D. Adams, must be a phenomenon belonging to the solid phase. This theory, moreover, is verified by the occurrence of the metamorphism of the olivine as well as of the plagioclase, attached to the *boundary plan* between the two minerals, not only where the olivine is to a great extent crystallized earlier than the plagioclase, but also where the plagioclase to a great extent crystallized earlier than the olivine.

3. The coronation occurs in rocks not dynamometamorphosed, and accordingly, as has been pointed out by earlier investigators, it is no function of any orogenic pressure.

4. The zones here treated I have observed in all of the very many microscopic thin sections that I have examined, of oliviniferous gabbros, norites, and anorthosites (with labradorite or still more basic plagioclase). In fact, the occurrence of the zones in these deep-seated rocks must be accepted as a general phenomenon.



FIG. 48.—Photomicrograph (24:1)

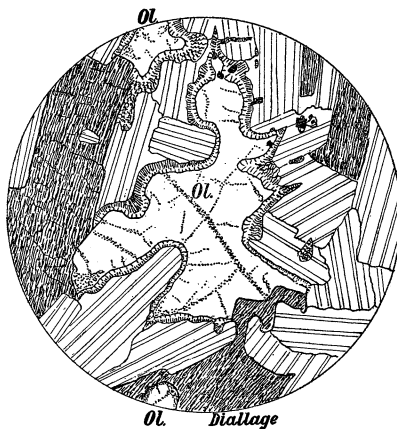


FIG. 49.—Drawing (24:1)

Hyperitic-structured olivine-gabbro from Elverum, Norway. Consists of *ca.* 65 per cent labradorite, 25 per cent diallage, 10 per cent olivine, traces of pyrite (in small cubes in the upper left portion of drawing). The labradorite laths show partial idiomorphism against the olivine (Ol.). Reaction rims between the olivine and the labradorite but not between the olivine and the diallage or between the labradorite and the diallage.

5. The thickness of the zones increases in the deep-seated rocks, as a general rule, proportionately to the amount of An contained in the plagioclase.

I cite: In the oliviniferous labradorite rock (Figs. 23–24) just mentioned (with Ab_1An_1) the total thickness of the zones regularly amounts to only 0.002 mm., sometimes to 0.005–0.010 mm., and exceptionally reaches 0.015 mm. In most olivine-hyperites (with plagioclase about Ab_1An_2), the thickness, as a general rule, is nowhere less than 0.06–0.08 mm.; most frequently it amounts to

0.10–0.12 mm., sometimes it reaches 0.15–0.20 mm., and quite exceptionally even rises to about 0.3–0.4 mm. In oliviferous rocks with bytownite, the thickness increases to a still larger amount, and exceptionally, in deep-seated rocks containing much basic plagioclase, the whole quantity of olivine may even be spent in forming the zones.

6. The total chemical composition of the zones is equivalent to the chemical composition of olivine plus plagioclase.

It should be particularly emphasized that the zone next the olivine consists of hypersthene, which may be chemically considered as olivine less half the contents of $\text{MgO} + \text{FeO}$, whereas the zone next the plagioclase consists of hornblende to which in most cases is added some spinel, which may be accounted for by the composition of the plagioclase with some addition of $\text{MgO} + \text{FeO}$.

The coronation of the olivine against the plagioclase—or, as it may be quite properly expressed as well, the coronation of the plagioclase against the olivine—is a phenomenon belonging to *the solid phase of the minerals after finished crystallization*. My son, Th. Vogt, state geologist, has pointed out to me that to these contact-new-formations the common physicochemical laws concerning the *reaction between two solid phases* are fully applicable.¹

This reaction is advanced by *high temperature*, and besides is a function of *time*. Therefore it must be assumed that the coronation began to take place immediately after the formation of the two minerals reacting on each other, and went on down to a certain limit of temperature (by way of example, 900°, 700°, 600°, or perhaps lower). The more slowly the cooling took place during the interval of reaction, the more the reaction was intensified. We accordingly always meet with reaction rims between olivine and basic or intermediate plagioclase in deep-seated rocks, but not—or to a much less degree—in the dike and effusive rocks which were more quickly cooled.

¹ See Beyschlag-Krusch-Vogt, *Erzlagertstättenkunde*, Vol. I (2d ed., 1914), p. 122. I beg to point out that the physicochemical laws for the reaction in the solid phase will no doubt throw quite a new light on numerous geologic processes, particularly on dynamometamorphism and contact-metamorphism. Upon these processes the influence of the varying relations of time, pressure, and temperature will particularly be felt.

The substances most easily soluble in acids generally have the greatest power of reaction. Therefore it is obvious that, as a general rule, the reaction rims should increase according to the amount of An contained in the plagioclase, as the solubility in acids of the plagioclase increases with its contents of An—and in plagioclase more basic than Ab_rAn_r the solubility increases obviously. Both olivine and basic plagioclase are much more easily soluble in acids than, for instance, the pyroxenes, the hornblendes, the micas, or the acid plagioclases. It is therefore easily accounted for that just between olivine and *basic* plagioclase the reaction rims are generally most strongly emphasized.

The general view here maintained of the reaction in the solid phase between olivine and plagioclase may in principle be transferred also on the corresponding reaction rims between diallage and basic plagioclase, between magnetite or titanomagnetite and plagioclase, etc..

[*To be continued*]